Long-range acoustic tracking of Antarctic blue whales

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ABSTRACT

The Southern Ocean Research Partnership (SORP) has developed an Antarctic Blue Whale Project which includes research to derive a mark-recapture abundance estimate for Antarctic blue whales. Tracking blue whales through passive acoustic monitoring has been identified as a potential means for increasing encounter rates, and thus facilitating abundance estimates through photo-identification and biopsy. This methodology was pursued by the Australian Antarctic Division (AAD) using DIFAR sonobuoys to detect, localise and track Antarctic blue whales on a research cruise from 140° E to 165° W, and south of 60°S between January and March 2013. Antarctic blue whales make loud and distinctive calls, known as 'Z' and 'D' calls. The loudest element of the 'Z' call (a 26Hz tone) was detected at a range of hundreds of kilometres. 26Hz calls were detected on all DIFAR sonobuoys deployed south of 52°S (n= 298). Whilst overlapping calls sometimes merged into a continuous tone, it was still possible to select individual calls which could be localised. Bearings from these vocalising whales allowed them to be acoustically tracked and targeted. Multiple sonobuoys were used to triangulate the location of individuals and groups. Received levels of detections increased with decreasing range to several acoustic 'hotspots' in the survey area, where whales were sighted. At these closer distances, full 'Z' calls and 'D' calls were also detected. 85% of acoustic targets resulted in visual encounters, yielding 32 encounters with groups of blue whales. The results demonstrate the ability of acoustic tracking to locate Antarctic blue whales that are widely dispersed over a large area as well as the capacity to acoustically track whales for days at a time. These abilities may assist with characterising their behaviour in their Antarctic feeding grounds. The results from this study may serve as a benchmark for future acoustic surveys of Antarctic blue whales, and may also be useful for quantifying the effects of acoustic tracking when designing future surveys.

KEYWORDS: ANTARCTIC BLUE WHALE, PASSIVE ACOUSTICS, SOUTHERN OCEAN, PHOTOGRAPHIC IDENTIFICATION

INTRODUCTION

During twentieth century industrial whaling, approximately 346,000 Antarctic blue whales (*Balaenoptera musculus intermedia*) were killed, resulting in the population being reduced by the 1970s to a small fraction of its pre-exploitation size (Branch 2007). The most recent estimate of population size was 2,280 (CV=0.36) in 1998 (Branch 2007), based on data from the IDCR-SOWER programme. However, there is still relatively little known about the extant population of Antarctic blue whales (Branch *et al* 2007).

The Antarctic Blue Whale Project (ABWP), a programme within the Southern Ocean Research Partnership (SORP 2009), aims to undertake research to quantify the recovery of Antarctic blue whales from near-extinction. A major research goal of the ABWP is to obtain an up-to-date estimate of circumpolar abundance of Antarctic blue whales. Additionally the project aims to describe population structure, explore linkages between breeding and feeding grounds, and characterise feeding and movement on the feeding grounds.

An assessment of methods for estimating Antarctic blue whale abundance indicated that mark-recapture (using photographic and genetic identification) may be the most cost-effective and practical approach (Kelly *et al* submitted). However, models indicated that these methods could only be practicable when visual observations were combined with additional survey methods that could improve the number of photographic and genetic captures over that expected from a standard line transect survey. Using passive acoustics to track and locate vocalising whales was proposed as a way to increase the number of captures (Kelly *et al* submitted).

All populations of blue whales make loud, low frequency (ie below 100 Hz) calls. Calls that are stereotyped and repeated at regular intervals are sometimes referred to as song, and it has been suggested that different populations have characteristic songs that are reasonably stable over timescales of at least 50 years (McDonald *et al* 2006; McDonald *et al* 2009). Blue whale song is thought to be produced only by males (McDonald *et al* 2001; Oleson *et al* 2007).

In contrast to song, frequency modulated ‘D’ calls, that are neither stereotyped nor repeated at predictable intervals, may be associated with group (McDonald *et al* 2001) and foraging behaviour (Oleson *et al* 2007). These ‘D’ calls, have been recorded in many populations/locations including the Antarctic (Rankin *et al* 2005) and from both sexes (Oleson *et al* 2007).

The calls comprising the song of Antarctic blue whales are called ‘Z’ calls because of their shape when viewed as a spectrogram (Rankin *et al* 2005). Each Z call is composed of three units that we label A, B and C (Figure 1). Unit A is a tonal and up to 10 seconds in duration. Unit B is a downsweep that follows immediately from unit A and is 1-2 s in duration. Unit C follows immediately from unit B and is a lower frequency tone that is sometimes slightly downswept and has a variable duration of a few to several seconds (Širović *et al* 2004; Rankin *et al* 2005).

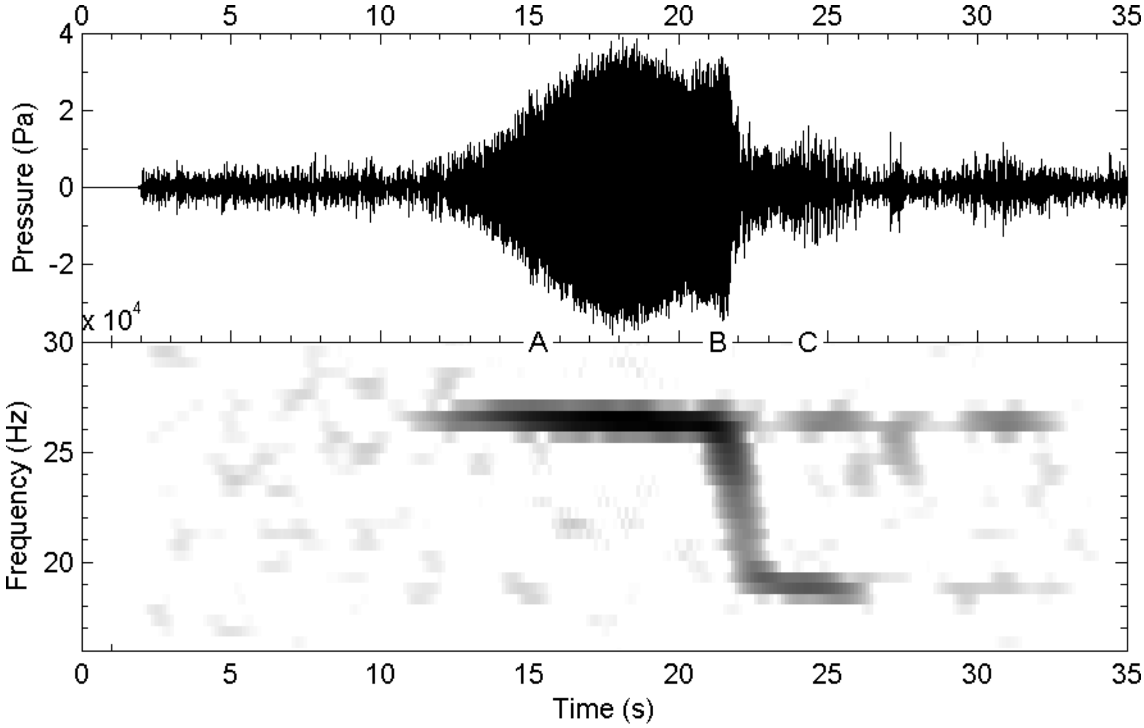

Figure 1 - Waveform and spectrogram of the stereotyped vocalisation made by Antarctic blue whales recorded in February 2013. This call is known as a Z call based on the characteristic shape of the call when viewed as a spectrogram. Spectrogram parameters: 250 Hz sample rate, 512 point FFT, 93.75% overlap between time slices.

Mean source levels of 189 dB re 1 µPa rms @ 1 m have been measured for Antarctic blue whale Z calls (Širović *et al* 2007), which were repeated at approximately 64 s intervals (Širović *et al* 2004). Due to the high source levels and low tonal frequencies, these sounds travel long distances underwater. Using equipment moored to the sea floor in deep Antarctic waters, Antarctic blue whales have been acoustically located at ranges of up to 200 km (Širović *et al* 2007). Additionally, Samaran *et al* (2010) reported detection ranges of Indian Ocean pygmy and Antarctic blue whales of up to 60 km from an array of hydrophones moored in subantarctic waters.

These long-distance detections suggested that real-time localization of blue whale vocalisations might provide an efficient means for finding blue whales. A trial voyage in 2012 lent support to this hypothesis, when pygmy blue whales were located using real-time passive acoustic tracking in Australian coastal waters (Miller 2012).

Data from the pilot study in 2012 were then used to model the performance of various survey designs for a dedicated voyage targeting Antarctic blue whales (Peel *et al* submitted). These models indicated that the use of real-time passive acoustics might yield an increase of two to four times the number of photographic captures of Antarctic blue whales compared to a pure visual transect (Peel *et al* submitted). However, these models required some assumptions regarding unknown aspects of the vocal behaviour of groups of Antarctic blue whales. One such assumption was an effective range of 30 km for detecting vocalisations of Antarctic blue whales. Another assumption was that 60% of the groups of whales vocalised, and that they did so continuously. Furthermore, sensitivity analysis revealed that the number of modelled encounters was most sensitive to the range of acoustic detections and the proportion of whales that were vocalising respectively (Peel *et al* submitted).

In 2013, the ABWP conducted the first Antarctic voyage to test and further develop acoustic tracking methods, as well as initiate collection of data that would lead to a contemporary abundance estimate for Antarctic blue whales (Double *et al* 2013). Here we present preliminary results of this voyage that are related to acoustic tracking of Antarctic blue whales, and we highlight aspects of this dataset that, with further analysis, should better quantify both the detection range of Antarctic blue whale vocalisations during real-time tracking, and the proportion of groups of whales that produce vocalisations. These results may lead to improved models for assessing survey design, and the practical information provided in this manuscript should be useful for those who wish to acoustically track blue whales. However, data presented here are preliminary, and a more detailed report including specific methods, further analysis of data, and detailed discussion of results and technical aspects of this work will follow later in 2013.

METHODS

Passive Acoustics

During the 2013 Antarctic Blue Whale Voyage, the main focus of the passive acoustics team was to direct the research vessel to groups of vocalising Antarctic blue whales. We searched acoustically for blue whales in daylight, darkness and in all weather conditions. Groups of whales that were detected and pursued were considered *target* whales, while those that were detected and acoustically monitored, but not pursued, were considered *tracked* whales.

The survey area was designated as the region west and north of the Ross Sea below 60°S between 135°E–170°W. Sonobuoys were deployed at 30 nmi intervals, or adaptively as needed during targeting and tracking. To facilitate the development of sound propagation models, CTD profiles were obtained at representative locations where possible.

Recordings of underwater sound were made using directional (DIFAR) sonobuoys. For this voyage we obtained a mixture of depassivated out-of-life HIDAR (SSQ 955) buoys (from Ultra Electronics Sonar

Systems, UK), out-of-life DIFAR 53D (from Australian Defence), and new DIFAR 53F sonobuoys (from SonobuoyTechSystems USA) to achieve a balance between reliability and affordability.

Signals from the hydrophones and sensors were broadcast over VHF radio (around 145 MHz) and received onboard the research vessel via an aerial at 21 m-above sea level. The recording chain for all sonobuoy deployments consisted of a WiNRaDiO G39WSBe VHF receiver with the voltage output calibrated as a function of modulation frequency. The raw voltage output of the receiver was connected to the instrument input of an RME Fireface UFX sound board with the gain set to 20 dB (*ie* full scale input voltage of 8.39 V peak-to-peak). The digitised signals from the UFX were saved as 16-bit WAV files with a 48 kHz sample rate using passive acoustic monitoring software PAMGUARD (http://www.pamguard.org, Gillespie *et al*, 2008). PAMGUARD also generated real-time spectrograms, while RME TotalMix software allowed the incoming audio to be monitored aurally. Additional commentary, recommendations, and practical advice on equipment, software and the use of these methods can be found in the Appendix.

Direction of whale calls

Audio clips of blue whale calls were saved separately from the raw audio stream for further processing in order to extract the direction of arrival of the call. This step was facilitated by a custom PAMGuard module that automatically created a WAV file containing the audio of any user selection made on the PAMGuard spectrogram window.

For each audio clip, DIFAR directional signals were demodulated using a version of Greenridge Science's demodulation software (http://www.greeneridge.com/software.html) running under Matlab version 7.0.2. The demodulator produced three binary files that represented the audio signals from the omnidirectional hydrophone and the two orthogonal directional hydrophones. These audio signals were low-pass filtered and resampled to reduce processor and memory demands for subsequent signal processing steps. Calls classified as blue whale vocalisations were resampled at a rate of 250 Hz, while all other calls, such as audio clips of the research vessel, were resampled at a rate of 4800 Hz.

The beamforming method described by McDonald (2004) was applied to the resampled signals in order to compute an ambiguity surface plot that showed beamformer power as a function of bearing and frequency. The spectrogram and the ambiguity surface plot were plotted side-by-side with identical frequency scales, allowing the operator to select the bearing that most clearly represented the signal of interest from the ambiguity surface plot. Typically this corresponded to the frequency bin of the sound source that contained the highest signal-to-noise ratio, rather than simply the peak energy. Care was taken by the operator to avoid frequency bins that also contained non-target noise sources as these could potentially bias the bearing towards the noise source and away from the target. Typical noise sources included the research vessel, other vessels, non-target whales, sounds from seismic airguns, and radio noise that occurred as VHF reception degraded with distance from the sonobuoy.

Sonobuoy compass correction

The magnetic compass in each sonobuoy was "calibrated" in order to obtain a correction that included the compass deviation and local magnetic anomaly (variation). The location of the sonobuoy deployment and the position of the vessel were collected via a GPS receiver. 10-second audio clips were then collected every 30 seconds as the vessel steamed away from the sonobuoy after deployment. Acoustically derived bearings to the research vessel, θ_a, were computed from these audio clips. The "true" bearings between the sonobuoy's deployment location and the vessel, θ_t, were also computed using the GPS onboard the vessel. The correction angle, θ_c, for each 10 second audio clip was computed as: $\theta_c = \theta_t - \theta_a$. Typically 15-20 measurements of angle θ_c were made as the vessel moved away from the sonobuoy, and the angular mean, $\bar{\theta}_c$, and standard deviation, σ_c, of these measurements were calculated. The sonobuoy was considered unreliable for bearing measurement if σ_c was greater than 10°. For reliable sonobuoys, $\bar{\theta}_c$ was used as a single correction that incorporated both the inherent error in the magnetic compass of the sonobuoy and the local magnetic variation.

Tracking and targeting

After the signal processing steps described above, the corrected bearing to whale calls was plotted on an electronic chart along with the position of the ship and deployment location of the sonobuoy. Groups of bearings that appeared to come from the same direction and had regular repetition rates were *tracked* as a group of whales that were then given a unique designation.

There were five main modes of acoustic operations, each corresponding to a different spatial scale. *Tracking* of groups of whales comprised logging the acoustic bearings of all groups of vocalising animals. Of these, only a small proportion were selected as good candidates for *targeting*, based on consistency of vocalising behaviour, proximity and logistical considerations. Long-range *targeting* involved deploying single sonobuoys at 30 nmi intervals and following an acoustic bearing (usually from a 26 Hz tone) towards a *target* group that was believed to be further than 30 nmi away. Close-range *targeting* mode involved deploying more sonobuoys in order to close in on individual vocalising whales believed to be within 30 nmi of the vessel. The fourth mode of operation was overnight *targeting*, which involved deploying sonobuoys to maintain an acoustic track of vocalising whales in order to position the ship within 10 nmi of blue whales by dawn when photo ID and biopsy effort could resume. The two main strategies for close-range and overnight targeting were 1) to deploy multiple sonobuoys to triangulate the position of a calling whale, and/or 2) to closely follow a bearing from a sonobuoy that was believed to be deployed less than 10 nmi from a whale. The final mode of operation, close-range *tracking*, occurred when the main vessel was with whales or in a close approach. During close-range *tracking*, the acoustics team deployed sonobuoys opportunistically in order to maintain an acoustic track of whales during sighting, photography, and biopsy attempts.

While *tracking* and *targeting* were conducted in real-time on the voyage here, for clarity, we include both information from the real-time analysis and also a summary of the directional information that has been post-processed. To obtain summary plots, kernel smoothing (Wand and Jones 1995) was applied to all the bearings to whale vocalisations per sonobuoy to yield a continuous *bearing density function* (BDF). Peaks in the BDF that were greater than a threshold value were selected as representative of a *tracked* group. The threshold value was computed per sonobuoy as $1/(2\sigma n)$ where σ represents the angular precision of bearings from the sonobuoy, and n was the total number of bearings obtained at that sonobuoy. The nominal angular precision of 10° as specified by the manufacturers was used as the value of σ for all sonobuoys.

Visual Observations

Visual survey for Antarctic blue whales was conducted during daylight hours concurrent with passive acoustic monitoring. During the 31 days within the survey area, 6078 km of visual survey effort was conducted over 346 hours. Visual surveys were conducted by observers on the open-air flying bridge and in the enclosed bridge, depending on weather environmental conditions; observers on the flying bridge alternated searching with naked eye and binoculars. Distance and angle relative to the ship of all visually detected cetaceans was measured using binoculars with reticles and angle boards. The visual search was curtailed when wind speeds were greater than 35 kts. This differs from the systematic line-transect IDCR SOWER circumpolar cruises where standardised survey conditions were limited to Beaufort <5 and a visibly clear horizon. Furthermore, the course of the vessel was always influenced by the available acoustic data. Hence none of the vessel's route could be considered as independent of knowledge of blue whale locations and was not intended to be used for design-based line-transect density estimation for blue whales.

Upon sighting whales, the vessel altered course to confirm species identification and obtain images for photo-identification. While approaching the sightings a system involving combined binoculars, video camera and still camera was used to obtain accurate locations of whales at the surface from photogrammetric measurements. This system is described in Leaper and Gordon (2001). Still images captured from video were used to measure the angle of dip from the horizon to the whale to measure distance, and images from a downward pointing still camera to obtain bearings relative to the heading of the ship.

RESULTS

The data presented in this report contain only outputs from 'real-time' acoustic data streams; investigation of the raw audio recordings will allow for both more detailed analysis and the development of additional methods in post-processing.

Number and type of sonobuoys used

260 sonobuoys were deployed in the study area in order to *track* and *target* whales, yielding 564 hours of acoustic recordings. On average slightly more than eight sonobuoys were used per survey day including transit. In practice, there appeared to be little difference in failure rate between the depassivated HIDAR and new 53F buoys (9% and 11% failures respectively). The 53D sonobuoys had a failure rate of 16% which was slightly higher than the other types, but these sonobuoys were by far the oldest, and most had been removed from hermetically-sealed packaging at least three years prior to this voyage.

Transit

Long-range detections of vocalisations from Antarctic blue whales were first noted during the transit to the study area on 3 February 2013 (sonobuoy #22, 51.95° S, 157.55° E). These detections comprised only a small portion of the unit A 26.4 Hz tone (the most intense unit of Z calls). By using spectral resolution of approximately 0.5 Hz, these 26.4 Hz tones were sufficiently distinct to distinguish them from pulsed vocalisations at 24 Hz produced by blue whales around New Zealand (as described by McDonald 2006); thus, the risk of misclassification was minimal. In New Zealand coastal waters, blue whales making the 'New Zealand' call type were also acoustically tracked, visually detected, and opportunistically photographed during the transits, to and from, the Antarctic study area (Miller *et al* 2013).

Antarctic blue whale vocalisations continued to be detected during the transit on all sonobuoys south of 52°S. Received levels of Antarctic blue whale vocalisations increased steadily in conjunction with latitude until approximately 58°S (Figure 2). The direction of Antarctic blue whale vocalisations was predominantly from the south during the transit. However around 57°S, vocalisations were detected from both the North and the South suggesting that we might have passed a group of vocalising Antarctic blue whales in the vicinity of 57°S (Figure 2). The intensity of calls dropped slightly after passing 58°S, and further analysis is required to determine whether this was a result of moving away from a northerly group of whales, or an effect of long range sound propagation from more southerly groups of whales. Received levels continued to increase as the vessel proceeded from 59°S to the south-western edge of the study area at 62°S. From there, received levels remained steady until we began to acoustically *target* Antarctic blue whales to the east.

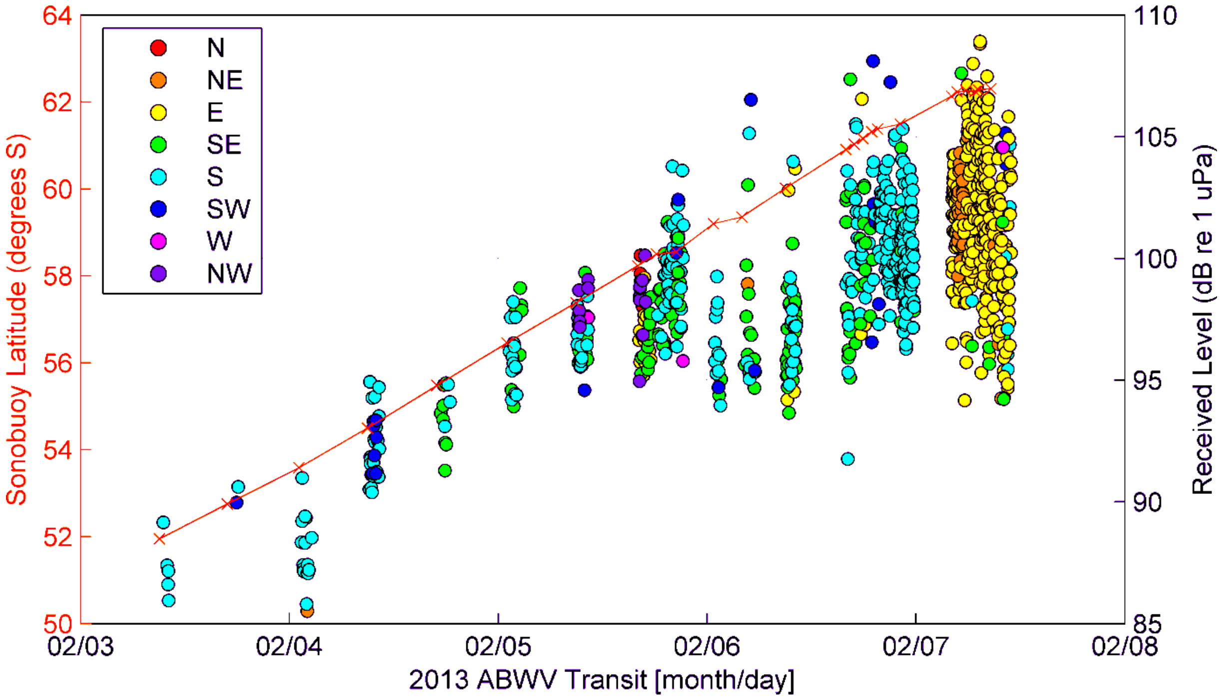

Figure 2 - Received levels of Antarctic blue whale calls detected during transit to the study area. The colour of the symbols indicates the direction of the calls. The red line with crosses shows the latitude of each sonobuoy deployment.

Table 1 - Acoustic tracking and targeting metrics while in transit and south of 60°S.

Measure	Transit to 60°S	Survey area	Total
Sonobuoys deployed	35	260	295
Number of failed buoys	7	31	38
Audio recorded (hours)	61.7	564.4	626.1
Audio from 2 simultaneous buoys (%)	19.1%	58.1%	54.1%
ABW calls analysed in realtime	539	26,006	26,545
Triangulated locations	0	3,146	3,146
Targets pursued	0	51	51
Targets successful	0	24	24
Acoustic associates	0	8	8
Targets aborted	0	13	13
Targets missed	0	6	6
Visual survey hours	64.1	346.6	410.7
Distance surveyed (km)	1,229	6,078	9,298

Survey Area

In the survey area, unit A of the Antarctic blue whale call (*ie* the 26.4 Hz tone) was detected on all 239 sonobuoys that were deployed. Entire Z calls (*ie* containing units A, B, and C) were detected on only 41% of sonobuoys. D calls were detected on 77% of sonobuoys. Detections of entire Z calls and detections of D calls appeared to be clustered near locations of encounters with Antarctic blue whales, while unit A was audible throughout the area south of South of 60°S and also during much of the transit (Figure 3).

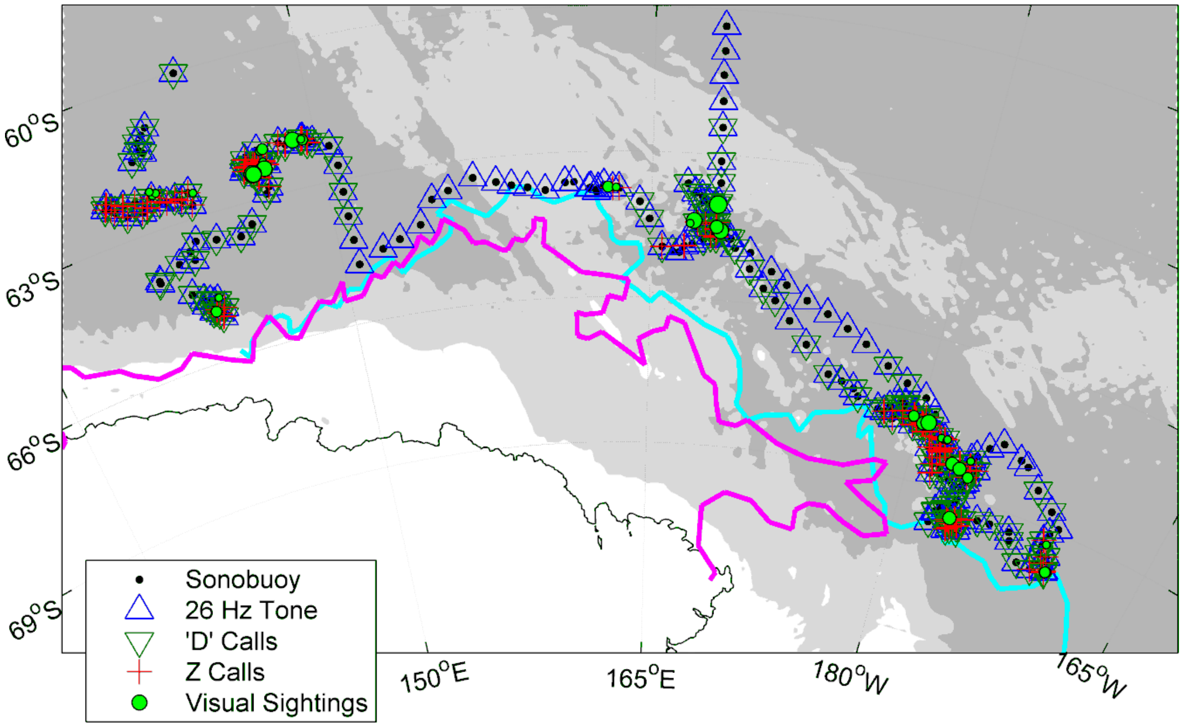

Figure 3 – Map of detections of Antarctic blue whale vocalisations the study area. 26 Hz tones (blue triangles) were detected on every sonobuoy deployed in the study area, while 'D' calls (green triangle), and Z calls (red cross), were detected only on sonobuoys that were nearer to visual sightings of whales. Gray shading indicates the 200 3000 and 6000 m depth contours from light to dark. Light blue and pink lines show the maximum and minimum extent of the ice edge as determined by AMSR2 sea ice images (http://www.iup.uni-bremen.de:8084/amsr2/).

51 groups of whales were *targeted,* of which 24 yielded visually confirmed encounters. In addition, eight attempts yielded encounters with Antarctic blue whales that were not the *targeted* vocalising whales, but were in close 'acoustic proximity' to, and thus believed to be *acoustically associated* with, the acoustically *targeted* whale (see the subsequent section on acoustic 'hotspots' for further explanation). Searches for 13 of the 51 *targets* were aborted. *Targets* were considered *aborted* when the *target* could still be tracked, but operational or environmental constraints prevented an approach to the whale. Eight *targets* were aborted in order to target whales that were believed to be closer; three *targets* were aborted due to difficult pack ice conditions that were not passable; one was aborted due to poor weather, and one *target* was aborted to continue visual survey in a different area. Finally, six of the *targets* were missed because the whale stopped vocalising and could no longer be acoustically located (Table 1).

The success rate of acoustic *targeting* was 84% and was computed as the number of *targets* and *acoustic associates* that yielded encounters with Antarctic blue whales divided by the total number of *targets. Aborted targets* were indeterminate and thus not considered when calculating success rate. Additionally, whilst not always explicitly recorded as distinct acoustic targets, there were several occasions where directional information provided by acoustic monitoring contributed to efficient, successful recommencement of visual contact with tracked whale(s) that had been inadvertently lost (due to poor sighting conditions, snowstorms, and/or fog).

Other species heard

In contrast to the constant acoustic presence of Antarctic blue whales, other species were detected intermittently (Figure 4). Acoustic recordings in the presence of other species took place on an opportunistic basis, and furthermore, detection and logging of other species during *targeting* and *tracking* of blue whales was possible only when it did not interfere with the primary objective of acoustically tracking Antarctic blue whales. Thus, the summary presented here is neither a complete nor thorough representation of the entirety of the recordings. However this map should serve as a good starting point for a more in-depth analysis. Notable recordings of other species during the voyage (apart from significant recordings of NZ blue whales) include sonobuoy #179 which was deployed near a group of fin whales, sonobuoy #323 which was deployed in the presence of a sei whale, and sonobuoys #245-254 which contain recordings of humpback whale social sounds.

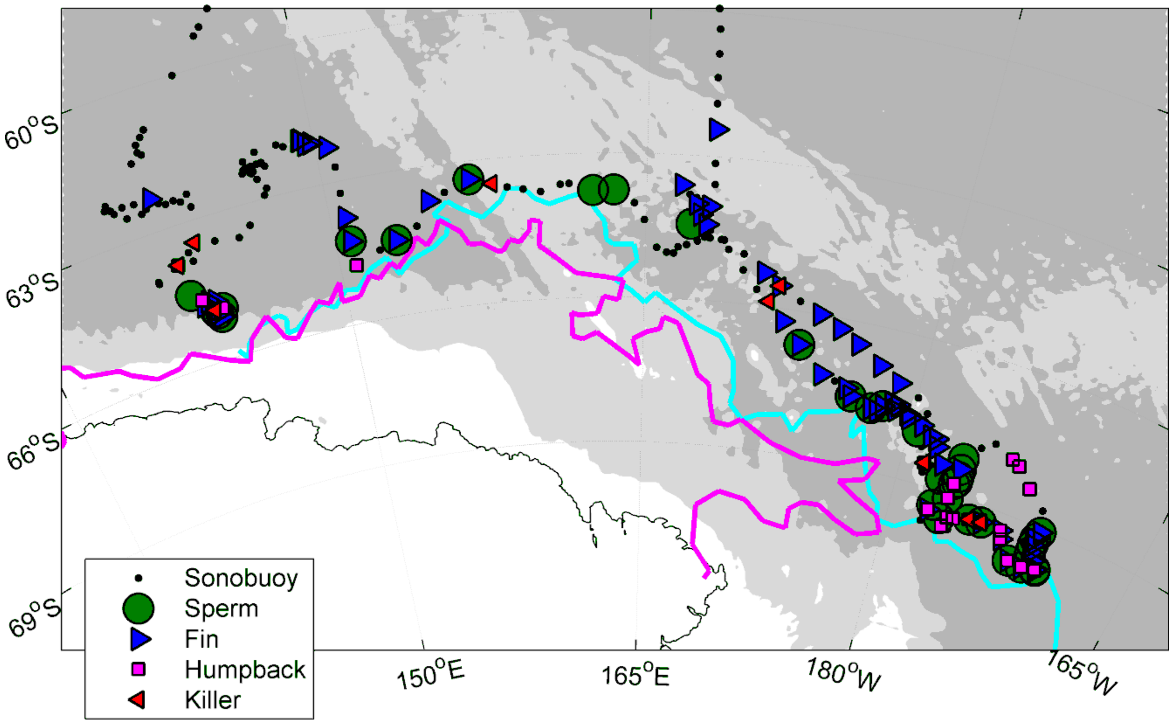

Figure 4 - Acoustic detections of sperm whale (green circle), fin whale (blue triangle), humpback whale (pink square), and killer whale (red triangle). Note: this map was generated using only preliminary detections during real-time monitoring and further analysis is required to confirm presence and absence of species presented here. Gray shading indicates the 200 3000 and 6000 m depth contours from light to dark. Light blue and pink lines show the maximum and minimum extent of the ice edge as determined by AMSR2 sea ice images (http://www.iup.uni-bremen.de:8084/amsr2/).

DISCUSSION

Changes in Antarctic blue whale calls

Previous studies of Antarctic blue whales have described the most intense part of Antarctic blue whale calls as a 28 Hz tonal vocalisation (Rankin *et al* 2005). More recently there has been documentation of annual decrease in the tonal frequency of blue whale vocalisations over several decades (McDonald *et al* 2009; Gavrilov *et al* 2011, 2012). During this voyage, the most intense (and most commonly detected) component of Antarctic blue whale vocalisations was a 26.4 Hz tone. Our observations of tonal frequency are in line with a simple linear extrapolation of the observations made by Gavrilov *et al* 2012. More detailed analysis is required to determine if there were any additional intra-seasonal changes in tonal frequency throughout the seven weeks of the study as was also found by Gavrilov *et al* (2012). Detailed investigation of differences in tonal frequency and duration of Z call units between individuals/groups is also planned.

Detection range of blue whale calls and acoustic 'hotspots'

While the 26 Hz tones were detected throughout the study area, the direction of these vocalisations was indicative of a handful of acoustic 'hotspots' within the study area that contained moderately-sized aggregations of whales, rather than a broad distribution of small groups of whales. These acoustic 'hotspots' are further supported by the fact that all visual sightings of blue whales were either acoustically *targeted* whales or believed to be associated with vocalising groups of whales. Measurement of the distance between *target* whales and *acoustic associates* was not straightforward, largely due to the facts that 1) these distances often exceeded the effective range of visual detections and 2) whales were constantly moving with respect to the vessel and eachother. A rought estimate of nominal distances between *acoustically associated whales* might be on the order of 10 nmi. However, further and more rigorous analyses are needed to compare estimates of group size based on acoustic and visual data.

Figure 5 shows several distinct acoustic 'hotspots' in the western, central, and southeastern parts of the area surveyed. Each of these hotspots was initially detected from distances of more than 100 nmi away. Furthermore, preliminary results suggest that the transits to and from the area south of 60°S are essentially extreme cases of long-range targeting; whale vocalisations from the most westerly (62°S, 140°E) and central hotspots (64°S, 170°E) were audible from approximately 600 nmi away during the transits. If these preliminary results are found valid, then these recordings may represent the largest detection range of any whale species obtained with a single hydrophone deployed near the sea surface. Although D and Z calls were not detected over the same distances as the 26 Hz tones, the fact that they were always detected at or near encounters with Antarctic blue whales suggests that they are excellent indicators of proximity to these acoustic 'hotspots' (Figure 3).

The lack of visual sightings of Antarctic blue whales outside of the identified acoustic 'hotspots' and extreme range over which Antarctic blue whale vocalisations were detected indicates that a high proportion of the whales within a large area would likely be detected acoustically. Hence there is considerable potential for further development of survey methods for Antarctic blue whales that optimise a combination of visual and acoustic survey techniques to generate estimates of abundance.

Factors that affect acoustic targeting

Weather

The acoustics team operated 24 hours a day for the duration of the voyage. There was only one day where weather and sea state affected acoustic operations, and this only resulted in a delay of a few hours between listening stations. Sonobuoy VHF reception and the signal-to-noise ratio of acoustic recordings were diminished above Beaufort sea state 6, yet even so, the quality of acoustic data at these times remained adequate, and therefore acoustic operations could continue under these conditions. Whilst fog and snow seriously impeded visual sighting efficacy, these conditions had minimal effect on acoustics operations, and on several occasions the acoustics team was able to advise on the search direction for the ship to successfully re-locate whales that had been visually detected and subsequently lost due poor sighting conditions such as fog banks and snowstorms.

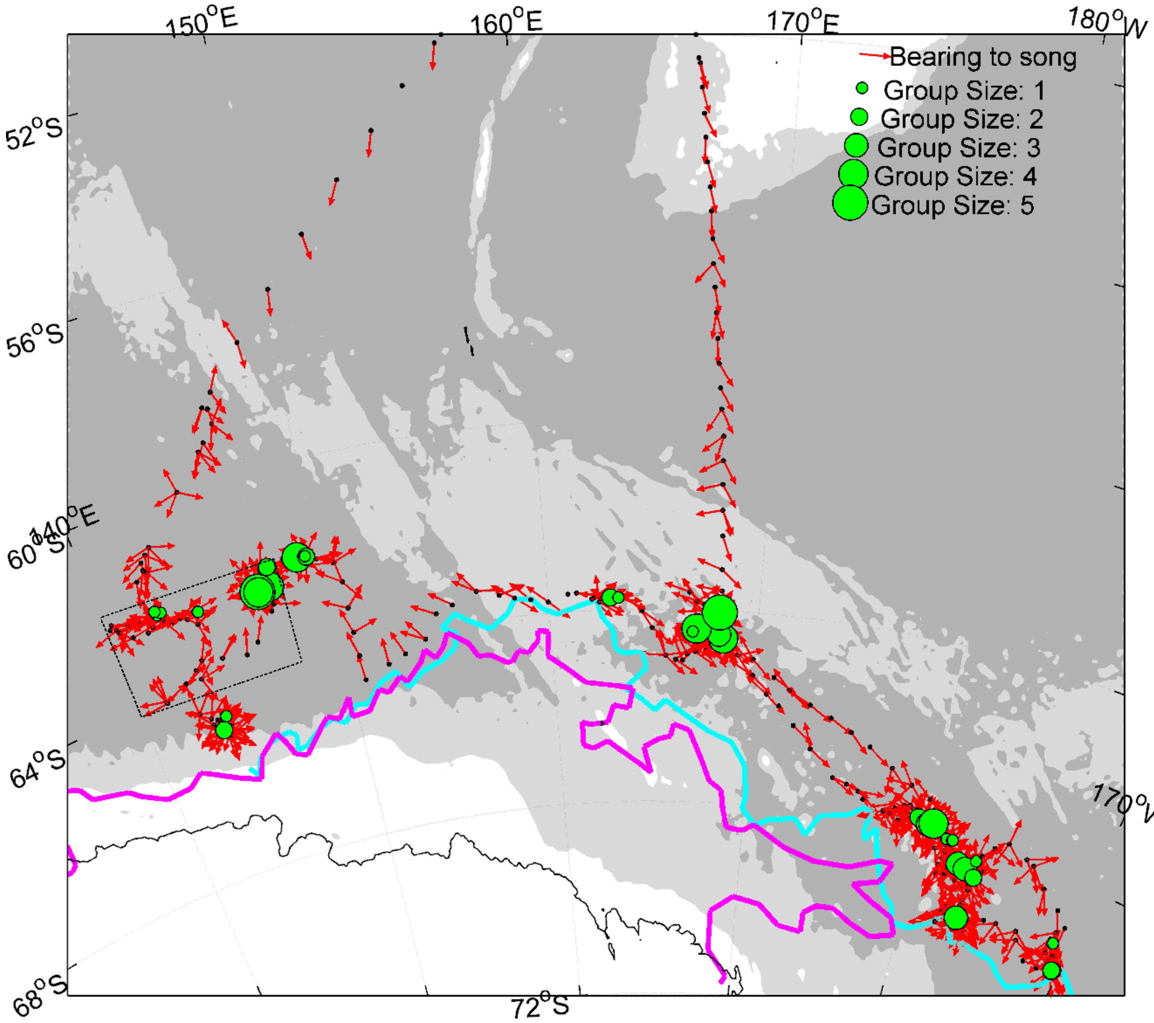

Figure 5 - Visual and acoustic locations of Antarctic blue whales during the 2013 voyage (including transit). Black dots show location of listening stations, while red arrows indicate the mean direction of clusters of Antarctic blue whale vocalisations. Visual sightings of blue whales are indicated by green circles. Real-time acoustic data from the area within black box is shown in detail in Figure 6. Gray shading indicates the 200 3000 and 6000 m depth contours respectively from light to dark. Light blue and pink lines show the maximum and minimum extent of the ice edge as determined by AMSR2 sea ice images (http://www.iup.uni-bremen.de:8084/amsr2/).

Magnetic South Pole

DIFAR sonobuoys contain a magnetic fluxgate compass that is used to measure the orientation of the directional acoustic sensors. The immediate proximity of the magnetic South Pole, (located on the western boundary of the survey area) resulted in substantial variation in magnetic declination over very small scales which presented a challenge for acoustic localisation using DIFAR sonobuoys. In the vicinity of the magnetic South Pole, extra measures were taken to ensure that the compass correction for each sonobuoy was reliable. These measures ('South Pole Protocol'), involved checking that the acoustically-derived bearing from the sonobuoy to the research vessel matched the actual bearing from the sonobuoy deployment location to the actual position of the vessel. If the acoustically derived bearing was incorrect, then an attempt was made to 'recalibrate' the sonobuoy by computing a new correction value for the sonobuoy compass. If two sonobuoys were deployed simultaneously, then time of arrival differences of relatively broadband sounds were used to further validate that acoustically derived bearings were still reliable. Finally, if no reliable bearings to the vessel could be obtained, then a buoy was declared unreliable and was no longer used for *targeting* or *tracking* whales.

Targeting strategies

Throughout the voyage, sonobuoys were deployed at intervals no greater than 30 nmi. During short-range targeting, it was necessary to deploy sonobuoys more frequently, with typical spacing of 12 nmi during a bearing search, and 8 -12 nmi for obtaining cross bearings. Both following a bearing line, and obtaining cross bearings proved to be successful strategies for locating whales at close ranges, and it should be noted that these methods are not mutually exclusive. Running bearing lines seemed to facilitate finding whales slightly faster when short-range targeting followed immediately on from long-range targeting. However, obtaining cross bearings proved to be more useful during overnight targeting as well as during acoustic tracking and close approaches. Figure 6 shows an example result that contains most of the different acoustic survey modes: *tracking, long range targeting, overnight targeting,* and *short-range targeting*.

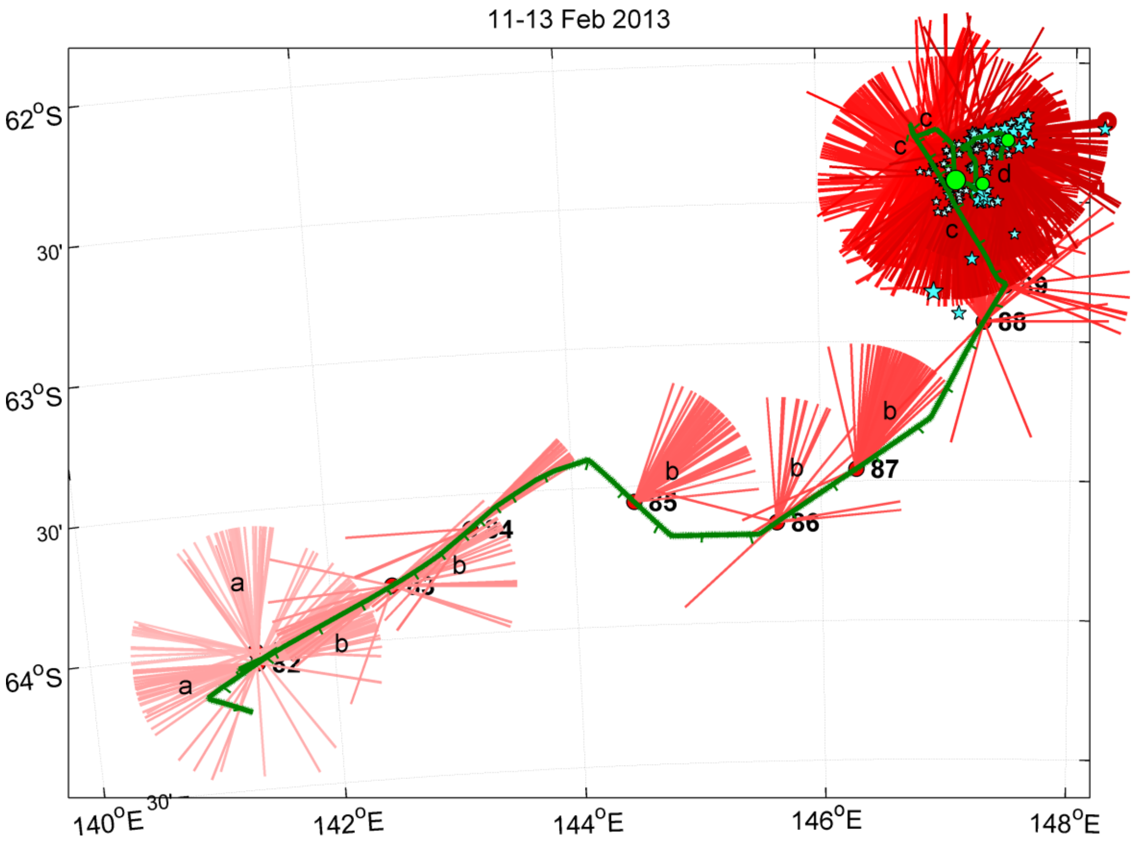

Figure 6 – An example illustrating various types of acoustic survey modes over a 48 period: (a) *tracking* (b) *long-range acoustic targeting* (c) *overnight targeting* and (d) *short range targeting*. The green line shows the ship's track (heading from southwest to northeast) with tick marks at one-hour intervals. Red circles show the locations of sonobuoys and black text indicates sonobuoy deployment number. Red lines show bearings to individual whale calls with lighter colours indicative of older bearings. The cluster of bearings in the northeast sweeps over a full 360 degrees: a typical result when deploying buoys amidst a group of whales. Blue stars show whale positions triangulated acoustically; green circles indicate visual sightings of blue whales.

In addition to the aforementioned targeting strategies, another key element of a successful scenario was patience. Upon arriving at the location of an acoustic target, environmental conditions such as darkness, fog, snow, or ice sometimes prevented the visual team from being able to detect or sample the acoustically targeted whales straight away. However, given the temporal and spatial scales involved in targeting a new aggregation, staying with a group which had already been acoustically located was often the most sensible option, even if this entailed waiting in the animals' location for several days. While further analysis is required to determine the proportion of time that blue whales spend vocalising, there were a number of occasions, especially overnight, when nearby whales went silent. In these instances, simply staying in the area and waiting for the next vocalisation proved a successful strategy, as the whales invariably resumed vocalising, albeit sometimes hours later.

Survey design

The fact that we are able to track vocalising Antarctic blue whales for days at a time presents additional opportunities for detailed observations of whales within an aggregation. Due to the dynamic nature of blue whale aggregations, it may take substantial time and concerted effort to obtain an accurate estimate of both the number of whales and the spatial extent of a group, as well as identification photos and biopsies of all individuals. Acoustic tracking of whales provides a means to stay with a group of whales as long as they continue vocalising in order to ensure capture of as many individuals within a group as possible. Combined with a gradual initial approach, this additional time with whales may allow whales to habituate to the research vessel, facilitating observations of undisturbed whale behaviour and may also mitigate against potential behavioural disturbances that may arise from close approach, thus further reducing the relatively minor impact of this non-lethal research.

In future studies, acoustic tracking could facilitate study of Antarctic blue whales over longer time periods, and this could provide the means to characterise their behaviour as well as ecological linkages and aid in the collection of additional environmental data (*eg* krill biomass, cetacean species community associations, oceanography and ice) over spatial scales that are relevant to blue whale ecology. The collection of such environmental data may yield a more complete ecological characterisation of Antarctic blue whale habitat as has been done for humpback whales in the western Antarctic peninsula (Nowacek *et al* 2011).

Furthermore, the ability to track and target whales over large areas and moderate time scales opens up an array of options for exploring efficient and opportunistic methods of finding Antarctic blue whales for the purposes of a mark-recapture abundance estimate. Combined visual and acoustic detection techniques such as conducting a structured, adaptive sampling visual transect survey throughout an 'acoustic hotspot' while simultaneously tracking vocalising whales may provide even better estimates of group size and spatial extent, which can in turn be used to optimise the amount of time spent obtaining biopsy and photographic identification samples. Furthermore, aerial surveys dropping sonobuoys from long-range aircraft (*eg* P3-Orion) could potentially provide a synoptic circumpolar view of acoustic hotspots, track whales from the sonobuoys, and fly over for estimates of group size. Alternatively, acoustic tracking and targeting of Antarctic blue whales could also be integrated into lower latitude cetacean surveys in Austral winter to target vocalising Antarctic blue whales that have migrated north during these months (Stafford *et al* 2004; Gavrilov *et al* 2012).

Further analysis (work-in-progress)

Further investigation into correlation between acoustic detections and the number of Antarctic blue whales within an 'acoustic hotspot' is presently underway. Further analysis of the fine structure of Antarctic blue whale calls is also ongoing and will focus on comparison of the duration and repetition rate of calls and units with older recordings of Antarctic blue whale sounds from IWC SOWER surveys as well as moored acoustic recorders.

Additionally, there were several occasions where sounds could unambiguously be attributed to photographically-identified (Olson *et al* 2013) and biopsied whales, thus comparison and characterisation of vocalisations both by gender and among individual whales will also be investigated. On several occasions concurrent video tracking and acoustic recordings were obtained. Further analysis of these recordings and video tracks is underway and will allow comparison of acoustic and visually observed behaviours. Analysis of simultaneous video (in particular, the video-derived range measurements) and acoustic data will also yield measurements of source levels of both blue whale song calls and 'D' calls.

CONCLUSIONS

Passive acoustic monitoring was extremely effective at long-range detection of Antarctic blue whales and also in precise guidance to the research vessel for successful achievement of close approach to Antarctic blue whales, irrespective of weather conditions. 26.4 Hz tones were detected throughout the study area, and on every sonobuoy deployed south of 52^{o}S. By using directional sonobuoys we were able to conduct long-range targeting of whales by following the direction of 26.4 Hz tones using only a single active sonobuoy per listening station. Following 26.4 Hz tones eventually led to the detection of D and Z calls, which, in conjunction with short-range targeting strategies ultimately led us to groups of vocalising Antarctic blue whales (Figure 3, Figure 5 and Figure 6).

Acoustic tracking provides for a fundamentally different kind of survey compared to previous design-based visual line transect sightings surveys such the SOWER surveys. The ability to track and target whales over large areas and long duration time scales opens up an array of options for exploring efficient and opportunistic methods of finding Antarctic blue whales for the purposes of a mark-recapture abundance estimate. Additionally, the ability to acoustically track whales for days at a time may help to characterise blue whale behaviour on their Antarctic feeding grounds.

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APPENDIX: RECOMMENDATIONS REGARDING REAL-TIME ACOUSTIC TRACKING

We expect that passive acoustic tracking will become a standardised method in future Antarctic blue whale research and offer the following practical guidance for those who intend to adopt these methods.

Sonobuoys

Whilst expired military sonobuoys are often generously provided to cetacean researchers, it is likely that the number of sonobuoys required for acoustic targeting may require the purchase of supplementary sonobuoys. Sonobuoy manufacturers require a lead-time of six months to one year, and obtaining an export license for sonobuoys in countries other their country of production can add additional delays. We recommend that future voyages planning to conduct acoustic targeting should secure as many sonobuoys as possible as far in advance of the voyage as practical. We recommend purchasing depassivated, out-of-life HIDAR (SSQ 955) sonobuoys. These sonobuoys have a good success rate and are smaller and lighter than 53D and 53F buoys. The smaller size and weight not only means less waste, but also reduced transport costs and easier handling. We recommend attempting to obtain a small number of GPS integrated sonobuoys. Such sonobuoys may provide accurate locations of the sonobuoy as it drifts, and in appropriate circumstances are likely to obtain more accurate measurements of source levels of sounds. However the increased cost of GPS sonobuoys may require a trade-off between fewer, but more accurate sonobuoys, or larger numbers of less accurate sonobuoys.

Recording chain

The utility of acoustic recording system is only as good as the weakest component. Since the hydrophone and radio transmitter within sonobuoys are standardised, and since the researcher will follow the above recommendation to secure as many sonobuoys as possible, the next potential point of failure lies within the receiving and recording system. We recommend investing in high quality VHF receivers capable of 20 kHz audio bandwidth and a flat frequency response. We had a good experience with WiNRADiO G39WSBe sonobuoy receivers. We had a good experience with VHF antenna model MFB1443 (3 dB gain; tuned to 144 MHz centre frequency) from PCTel Inc. (http://www.antenna.com). We recommend using high quality VHF preamplifiers placed as close to the VHF antenna as possible and using low-loss cable to connect preamplifiers to VHF receivers. We had good experience with Minicircuits ZX60-33LN-S+ amplifiers and LMR400 cable. We recommend that the VHF antenna be placed as high as possible on the research vessel in order to obtain the greatest radio horizon. Ideally the antenna should be isolated from other communications equipment such as RADAR, other radios, and physical obstructions. For this voyage the antenna was placed at the top of the gantry, which was approximately 21 m high. We recommend avoiding VHF transmitters for shipboard communications and suggest using handheld UHF radios as a potential replacement.

In addition to sonobuoys, we recommend having a variety of recording devices for opportunistic recording of other species. We recommend considering a towed array in order to better survey for sperm whales and beaked whales, particularly if a relatively quiet vessel is being used for the research. We recommend considering calibrated hydrophones with portable recording devices for both the research vessel and small boat in order to record humpback, fin, and killer whales as well as pinnipeds.

Real-time analysis and targeting

We recommend further development of the real-time analysis software in order to simplify and automate analysis where possible. Particular improvements include: 1). Integration of software programs into a single program. 2). Development of a classifier to allow automatic detection of Z calls and 26 Hz tones. 3). Integration of sightings, acoustic detections, radar, AIS, ice imagery, and position/track of research vessel into a single real-time display and database. Presently many of the Matlab algorithms used in this study are being integrated into a PAMGuard module, which should go some way towards addressing these recommended improvements.

Practice and experience

The extensive experience of the acoustics team was a major factor that contributed to the high number of successful tracks. In addition to assembling a highly experienced team, we recommend conducting trial voyages to test equipment and protocols before embarking upon a long Antarctic survey, ideally on the same vessel that will be used in the Antarctic. No significant acoustic monitoring time was lost on this trip due to hardware or software problems or failures. This can be partly attributed to a system that was thoroughly tested on trial voyages.